NASA TECHNICAL NOTE

NASA TN D-2117

NASA TN D-2117

EVALUATION OF SHOCK-TUBE HEAT-TRANSFER EXPERIMENTS TO MEASURE THERMAL CONDUCTIVITY OF ARGON FROM 700° TO 8600° K

by Milton R. Lauver

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • FEBRUARY 1964

EVALUATION OF SHOCK-TUBE HEAT-TRANSFER EXPERIMENTS TO MEASURE THERMAL CONDUCTIVITY OF ARGON FROM 700° TO 8600° K

By Milton R. Lauver

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Office of Technical Services, Department of Commerce,
Washington, D.C. 20230 -- Price $0.50

EVALUATION OF SHOCK-TUBE HEAT-TRANSFER EXPERIMENTS TO MEASURE THERMAL CONDUCTIVITY OF ARGON FROM 700° TO 8600° K

By Milton R. Lauver

Lewis Research Center

SUMMARY

Recent studies of heat transfer to a solid from a hot stagnant gas behind reflected shock waves have been interpreted to obtain the thermal conductivity of the gas or its integral with respect to temperature. The interpretations are critically compared with each other and with new experimental data from argon shock-heated to 8580° K. The surface temperature rise of heat-resisting plate glass suddenly exposed to hot argon was predicted and experimentally verified to the limits of the test. Variations of several percent in the theoretical assumed thermal-conductivity values of argon had little effect on the temperatures predicted. Within these limits, theoretical values of thermal conductivity for argon were experimentally verified.

INTRODUCTION

The transport properties of gases at high temperatures have recently become of interest. At the higher temperatures, direct equilibrium-type measurements are not generally practical. The shock tube has been considered as a tool for the determination of one transport property, thermal conductivity, at high temperatures.

In the region of stagnant gas behind a shock wave reflected from the end of a shock tube, temperatures up to several thousand degrees Kelvin are reached very quickly and are maintained constant for tens of microseconds. The surface temperature of the end wall rises only a few degrees, because in such a short time the solid is effectively a large heat sink (ref. 1).

Consideration of the thermal relations between the surface of a semi-infinite solid and a semi-infinite contiguous body of gas at the same temperature that is suddenly raised to a much higher uniform temperature suggested that the thermal conductivity of the gas at the higher temperature could be obtained by the proper analysis of such data.

This type of analysis has been applied to data obtained behind reflected shock waves in argon, and thermal conductivities at temperatures from 1000° to 3300° K have been reported (ref. 1). The investigation of reference 1

extended the range of previously reported experimental values by nearly 2000° K. Excluding calculations based on molecular beam scattering data, the data of reference 1 have been the highest temperature experimental results available. The problem of determining the thermal conductivities of air from data similarly obtained has also been considered. In references 2 and 3 the heat-conduction equation is solved, not for thermal conductivity as done in reference 1, but for the integral of thermal conductivity, or the heat-flux potential, as a function of temperature. It was concluded that, while the thermal conductivity could be approximately obtained from values of the integral reported, the differentiation of the data involves considerable loss of accuracy.

Improved experimental techniques and instrumentation were applied in reference 4 to extend the work with air of references 2 and 3. The analysis to determine the heat-flux potential from the experimental data was extended to include nitric oxide formation and nitrogen dissociation. In reference 5 the analysis and data of reference 2 were examined. An important factor attributable to the motion of the hot gas toward the cooler wall had been overlooked, so the analysis was revised.

The purposes of this investigation were as follows:

(1) To obtain data on the temperature rise of the end wall of a shock tube for argon over an extended range of reflected shock temperatures

(2) To resolve the differences others have expressed in the interpretation of such data

(3) To determine whether such shock-tube data can be used to compute thermal conductivities of gases or to confirm theoretical estimates of thermal conductivity

THEORY

Assumptions

It is assumed that a quiescent gas at thermal equilibrium in a tank is suddenly heated to a uniform temperature greater than that at a plane end wall. Both the gas and the end wall are semi-infinite in extent so that conditions are at all times uniform over any plane parallel to their interface. The solid, initially at a uniform temperature throughout, has density, specific heat, and thermal-conductivity properties that are independent of temperature and pressure over the ranges of interest. The gas properties at any point have equilibrium values that are dependent on temperature and pressure. Viscous dissipation is assumed to be negligible. Heat transfer from the gas, which has been heated by reflection of a strong shock wave from the solid end wall, is assumed to be unaffected by the presence of the receding reflected shock wave.

Equations

The partial differential equation that describes one-dimensional heat flow

by conduction at constant pressure with the assumptions noted previously is

$$c_p\rho \frac{DT}{Dt} - \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) = 0 \tag{1}$$

where c_p is specific heat per unit mass, ρ is density, T is temperature, t is time (from the instant the gas is heated), x is the coordinate extending normally into the gas from its origin at the interface, k is the coefficient of thermal conductivity, and D/Dt is the substantial derivative.

In reference 1 T_f is defined as the temperature asymptotically approached by the interface and ρ_f as the density of the gas at T_f and the constant pressure of the hot-gas column. The thermal conductivity of the gas at T_f is k_f. The subscripts used are 0 for the initial conditions before the gas is heated, ∞ for the conditions immediately after heating, and s for the constant properties of the solid. For $T_f - T_0 \ll T_\infty - T_0$, as in this case, with k a linear function of temperature and with the definitions

$$h \equiv \int_0^{x(h,t)} \frac{\rho}{\rho_f}\, dx$$

$$a_f \equiv \frac{k_f}{\rho_f c_p}$$

and

$$\xi \equiv \frac{h}{2\sqrt{a_f t}}$$

equation (1) is transformed into

$$\frac{d}{d\xi}\left(\frac{k}{k_f}\frac{T_f}{T}\frac{DT}{d\xi}\right) + 2\xi \frac{DT}{d\xi} = 0 \tag{2}$$

If T is expressed as a function of ξ and the limits $T(0) = T_f$ and $T(\infty) = T_\infty$ are used, a low value of $(dT/d\xi)_{\xi=0}$ or $T'(0)$ may be chosen and T_∞ may be numerically calculated with known values of k. A value of $T'(0)$ can be chosen so that it would be necessary to supply a value of k slightly beyond the known ones. At $\xi = 0$, $dT/d\xi$ is related to $T_f - T_0$ and, hence, to the experimental T_∞ by equation

$$T_f - T_0 = \frac{\sqrt{\pi}}{2}\left(\frac{\rho_f c_p k_f}{\rho_s c_s k_s}\right)^{1/2} T'(0) \tag{3}$$

The chosen value of k beyond the known ones must be such that T_∞ calculated with it equals the T_∞ found experimentally.

The studies of references 2 and 3 were limited to air. An analysis for

inert gases is given in references 2 and 3 along with modifications that provide for its application to chemically reactive gases such as air. The defining equations used for inert gases were

$$a \equiv \frac{k}{\rho c_p}$$

$$\varphi \equiv \int_0^T k \, dT$$

$$p \equiv \rho R T$$

and

$$y = \frac{x}{2\sqrt{a_0 t}}$$

With some manipulation, the starting equation

$$\rho c_p \frac{\partial T}{\partial t} - \nabla(k \nabla T) = 0$$

became

$$\varphi \frac{d^2\varphi}{dy^2} + 2y \frac{d\varphi}{dy} = 0 \tag{4}$$

At $x = 0$, for the solid,

$$T_f - T_0 = \frac{\sqrt{\pi}}{2} \left(\frac{a_s}{a_0}\right)^{1/2} \frac{\varphi'(0)}{k_s} \tag{5}$$

If φ is expressed as a function of y with the boundary conditions

$$\varphi(0) = 1$$

and

$$\lim_{y \to \infty} \varphi = \varphi_\infty$$

and the value of $(d\varphi/dy)_{y=0}$ or $\varphi'(0)$ calculated from equation (5), the value of φ_∞ can be found by numerical integration; φ_∞ can be differentiated to get k_∞.

In the study of reference 5 it was concluded in reference 2 that an important source of heat transport to the end wall had been overlooked. The temperature of the end wall rises very little by comparison with the temperature of the body of gas during the short testing time available. Since the solid acts as a large heat sink, the gas temperature and the properties of the gas

affected by temperature are changed as the solid surface is approached. In addition, the cooling effect of the solid extends into the gas, and thus its density at the constant pressure of the gas column increases. The increasing density sets up a net flow of gas molecules toward the solid, changes the temperature gradient there, and assists the conduction of heat. This additional contribution to the heat flux, not considered in references 2 and 3, was found to be appreciable.

Reference 5 uses the same defining equations as references 2 and 3 but also the following equations of continuity and momentum:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) = 0$$

and

$$\rho \frac{Du}{Dt} = -\frac{\partial p}{\partial x}$$

and a third defining equation $\psi(y) \equiv ut/x$. The average particle velocity in the gas is u. The working equations that developed then from equations (1) and (4) are

$$\frac{a}{a_0}\frac{d^2\varphi}{dy^2} + 2y\frac{d\varphi}{dy}(1 - 2\psi) = 0 \tag{6}$$

and

$$\frac{d\psi}{dy} + \frac{\psi}{y} = -\frac{1}{2\rho}\frac{d\rho}{d\varphi}(2\psi - 1)\frac{d\varphi}{dy} \tag{7}$$

For the solid at $x = 0$,

$$T_f - T_0 = \frac{\sqrt{\pi}}{2}\left(\frac{1}{a_0 \rho_s c_s k_s}\right)^{1/2} \varphi'(0) \tag{8}$$

The boundary conditions are $\varphi(0) = 1$, $\lim_{y \to \infty} \varphi = \varphi_\infty$, $\psi_{y=0} = 0$, and $\psi_{y \neq 0} \neq 0$. After a value is chosen for $T_f - T_0$, and hence $\varphi'(0)$, values of T_∞ and φ_∞ are the result of the numerical integration. With the restriction of $\psi = 0$, the equations are the same as those of references 2 and 3.

It may be noted that the term $T'(0)$ of reference 1 (eq. (3)) is related to the other similar limit terms as follows:

$$T'(0) = \left(\frac{dT}{d\xi}\right)_{\xi=0} = \frac{1}{k_f}\left(\frac{d\varphi}{dy}\right)_{y=0}$$

APPARATUS AND PROCEDURE

Shock-Tube Apparatus

The shock tube that was used is illustrated in figure 1. The high-pressure chamber is a 6-foot-long steel tube capable of withstanding pressure greater than 8000 pounds per square inch gage. It has an inner diameter of 1.85 inches. The low-pressure chamber is rectangular, $2\frac{7}{8}$ by 3 inches in cross section; it is made up of 3-foot-long interchangeable subsections. Each subsection is composed of two 1/2-inch-thick steel plates, used as vertical sidewalls, bolted to a top plate and a bottom plate, each $1\frac{7}{8}$ inches thick. Six subsections were used in this study. They were terminated at a pressure-relief tank that is 5 feet in diameter and 12 feet long.

The high-pressure chamber was separated from the low-pressure one by a diaphragm sheet of aluminum or polyester plastic. The pressure in the high-pressure chamber was gradually increased until the diaphragm ruptured. The aluminum diaphragms were scored with a cross to about one-third of their depth to ensure their rapid opening and to prevent the loss of fragments. The plastic sheets were not scored. A second, thin, 0.00097-inch-thick sheet of polyester plastic separated the low-pressure chamber from the evacuated relief tank. This diaphragm broke on the arrival of the shock wave created by the breaking of the first diaphragm. The low-pressure chamber was thus relieved of all pressures higher than atmospheric immediately after the passage of the shock wave, the system as a whole (with both diaphragms broken) being at less than atmospheric pressure.

Shock Velocity Measurements

The shock Mach number was determined from the time required for the shock wave to travel between two pressure detectors mounted 12 inches apart near the end of the shock tube. The upstream detector at station 2 was $17\frac{1}{2}$ feet from the main diaphragm. A barium lead titanate piezoelectric element was used for the active part of the detectors.

Resistance-Thermometer Mounting

Concentrically mounted in the shock tube at station 5 was a four-lead thin-film resistance thermometer on a heat-resisting glass plate (fig. 2). A stainless-steel tube clamped it rigidly into place. This guard tube, honed inside to minimize boundary-layer effects, made the conditions optimum for normal reflection at the glass plate.

The external shaping of the guard tube minimized the effect of pressure loading from shock waves on the glass-plate assembly. With this mounting, the temperature measurement was completed before the shock wave, passing externally to the guard tube and glass-plate assembly, could affect the results. The

recording oscilloscope was triggered a few microseconds before the arrival of the incident shock wave by an internally mounted piezoelectric element at station 4.

Resistance-Thermometer Films

A rectangular piece of heating-resisting plate glass served as the base for the film. One side was grooved to accept the electrical leads. The grooves were coated with a thin film of a metallo-organic solution containing 4.25 percent platinum and 3.25 percent gold. The resistance film itself was drawn with a pen filled with the platinum fluid. The glass was then heated to 800° F, held there for about 1/2 hour, heated to 1200° F, held there for about 1/4 hour, and removed to room temperature. The platinum film thus formed was then coated with a layer of silicon monoxide by vacuum evaporation. The glass plate was held at 1000° F overnight to oxidize the silicon monoxide to the dioxide. The thickness of the platinum film prepared in this manner was about 0.1 micron or 10^{-4} millimeter. The thickness of the silicon monoxide layer was 2×10^{-4} millimeter based on its voltage breakdown, 200 kilovolts per centimeter (ref. 6).

The four lead wires were soft soldered to the grooves in the glass plate to complete the circuits shown in figure 3. The portions of the electrical circuit that were exposed in the shock tube and that were not electrically insulated from the test gas by the silicon dioxide film were coated with a thin layer of a polyacrylic insulating lacquer.

The resistance film thermometer was then calibrated in a water bath to determine its temperature coefficient of resistivity, 0.0027 ohm/(ohm)(°C). The physical properties of the heat-resistant glass were used as $a_s = 0.0057$ square centimeter/second and $k_s = 0.0024$ calorie/(centimeter)(degree)(second), as in reference 2.

Procedure

The low-pressure chamber of the shock tube was twice evacuated to a pressure of less than 0.1 millimeter of mercury and filled with argon to over 100 millimeters of mercury. After a third such evacuation, it was filled to the desired pressure. Helium was then gradually added to the high-pressure chamber until the diaphragm burst.

The speed of the shock wave was determined between stations 2 and 3 with an electronic timer accurate to 0.5 microsecond. The average attenuation in speed over this 12.0-inch distance was found by measuring the speed of several shocks between stations 1 and 2 and between stations 2 and 3.

A constant electrical current flow of 1 milliampere was maintained through the resistance-thermometer film. The temperature changes were calculated from the deflection registered on a differential oscilloscope operated at a vertical gain of 2 millivolts per centimeter at a sweep speed of 5 microseconds per centimeter.

Data Reduction

The average incident shock-velocity attenuation was found to be 4.5 percent per foot in test section 6. The incident shock velocity at the end wall was determined by extrapolation from an upstream velocity measurement.

The reflected shock temperature and pressure were determined by incident shock-velocity relations. The temperatures ranged from 665° to 8580° K and the pressures from 0.31 to 13.7 atmospheres.

A typical oscilloscope photograph is given in figure 4. By a change in the ordinate scaling factor, the smoothed traces of all the other oscilloscope data could be superimposed on this one to coincide at 0 and 4 microseconds after the arrival of the shock. In this event, the traces differed by a maximum of ±5.5 percent at 15 microseconds and by lesser amounts at earlier times.

The individual photographs were measured with a traveling microscope. A linear plot of the oscilloscope voltage deflections of the sample trace against the reciprocal square root of the time t after arrival of the shock (fig. 5) yielded a straight line for several microseconds, centered around 4 microseconds (ref. 1). In the derivation of equation (3) for temperatures other than T_f, the right side of the equation is multiplied by the factor $1 - e^{\rho_s c_s k_s t/\lambda^2} \operatorname{erfc}\left(\sqrt{\rho_s c_s k_s t}/2\right)$, where λ is the heat capacity per unit area of the resistance thermometer. For a range of times where

$$\frac{\sqrt{\rho_s c_s k_s t}}{\lambda} \gg 1$$

the factor simplifies to $1 - \lambda/\sqrt{\pi \rho_s c_s k_s t}$ and therefore the temperature rise is directly proportional to $1 - \text{constant}/\sqrt{t}$. The voltage deflections obtained by extrapolating the straight line to zero on the abscissa (infinite time) were proportional to the asymptotic temperature changes $T_f - T_0$. These were calculated for each trace by multiplying the temperature change at 4 microseconds by the average deflection factor, 1.48.

RESULTS AND DISCUSSION

When the procedure of reference 1 was followed to get k from T_∞ and $T_f - T_0$, it became evident that the inevitable small errors in the determination of either parameter resulted in intolerably large changes in the values of k that satisfied the equations. Because of this difficulty, attention was shifted to other methods of analysis.

When the more difficult problem of the reacting gas mixture air was considered (refs. 2 and 3), similar shock-tube data were used to calculate the heat flux potential φ. The integral φ is less sensitive to the experimentally measured properties than k. The experimental results of references 2 and 3 were left in a dimensionless integral form because of the increase in uncertainty involved in determining the derivative k.

In the study of reference 5 estimated values of k for air were used to calculate the $T_f - T_0$ change at various T_∞ values by the analysis of reference 5 and by the previous analysis (ref. 2), which did not consider heat transfer by gas movement toward the cool wall. The experimental data for air agree more accurately with the analysis of reference 5.

Scrutiny of the Lagrangian transform used in reference 1 showed it to be a form of the continuity equation $(\rho/\rho_0)dx = dx_0$ (ref. 7), where $dx_0 = dh$ and $\rho_0 = \rho_f$. For heat transfer considered to take place at constant pressure, references 1 and 5 used the same premises.

In a comparison of the results with the analyses of references 1, 2, 3, and 5, the $T_f - T_0$ rise for plate glass was predicted for each method of analysis with high-speed digital computer programs. Table I lists the thermal-conductivity values for argon that were supplied to the computer. They were estimated from experimental viscosity data, thermal conductivity data, and molecular beam scattering data. The temperature-rise results are plotted in figure 6.

The results of the analyses of references 1 and 5 were the same, which verified the expectation that the use of the same premises would lead to the same solutions even though the final equations were expressed in different forms and required different computer programs. The analysis of references 2 and 3 predicted a much smaller rise in temperature. The experimental data listed in table II and plotted in figure 6 are much closer to the predictions of the analyses of references 1 and 5. The $T_f - T_0$ results are each divided by the square root of the corresponding reflected shock pressure to normalize its effect on the temperature-rise correlation.

To show the sensitivity of the temperature-rise predictions to the choice of thermal conductivity data used, the temperature increases were recalculated according to the methods of references 1 and 5 with a Sutherland-type expression for thermal conductivity, which is based on viscosity measurements below 2000° K. According to modern kinetic theory, the Sutherland expression presents a lower limit of credible values of high-temperature thermal conductivity. It results in thermal conductivity values the same as those from other expressions at the lower temperatures but differs by giving progressively greater values at higher temperatures. The change is -20 percent at 5000° K and -31 percent at 10,000° K. As shown in figure 6, the predicted temperature rise is lowered by 1.8 percent at 5000° K and 4.9 percent at 10,000° K. From another viewpoint, an error of 0.2° K in the measurement of $T_f - T_0$ (at 1 atm) or of 100° K in the measurement of T_∞ at 5000° K is equivalent to a change in k of 20 percent.

Ionization of the argon would have caused the heat-transfer results to be in error. Reference 8 indicates the ionization is negligible even at the highest Mach number reached in this work.

CONCLUSIONS

The temperature rise of a glass end plate exposed briefly to argon at 665° to 8580° K and at pressures ranging from 0.31 to 13.7 atmospheres was found

experimentally to be consistent with that described by the analyses of references 1 and 5. An analysis similar to these, but that omitted the continuity equation from consideration, predicted much too small a temperature rise.

A large deviation in thermal-conductivity values used to calculate the temperature rise analytically had only a small effect on the result. This has made it impractical for the experimental data thus far developed to distinguish between rival theoretical thermal-conductivity values that differ by only a few percent. The data have shown experimentally, however, that to about 8600° K the theoretical thermal-conductivity values for argon presented herein are approximately correct.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, September 25, 1963

REFERENCES

1. Smiley, E. F.: The Measurement of the Thermal Conductivity of Gases at High Temperatures with a Shocktube; Experimental Results in Argon at Temperatures Between 1000° and 3000° K. Ph.D. Thesis, The Catholic Univ. of Am., 1957.

2. Hansen, C. Frederick, Early, Richard A., Alzofon, Frederick E., and Witteborn, Fred C.: Theoretical and Experimental Investigation of Heat Conduction in Air, Including Effects of Oxygen Dissociation. NASA TR R-27, 1959.

3. Hansen, C. Frederick: Heat Diffusion in Gases, Including Effects of Chemical Reaction. ARS Jour., vol. 30, no. 10, Oct. 1960, pp. 942-946.

4. Peng, Tzy-Cheng, and Ahtye, Warren F.: Experimental and Theoretical Study of Heat Conduction for Air up to 5000° K. NASA TN D-687, 1961.

5. Thomson, T. A.: Heat Transport to a Solid Wall from a Suddenly Heated Gas. Aerodynamics Note 186, Aero. Res. Labs., Nov. 1960.

6. Marrone, P. V., and Hartunian, R. A.: Thin-Film Thermometer Measurements in Partially Ionized Shock-Tube Flows. Phys. of Fluids, vol. 2, no. 6, Nov.-Dec. 1959, pp. 719-721.

7. Milne-Thomson, L. M.: Theoretical Hydrodynamics. The Macmillan Co., 1955, pp. 76-77.

8. Lin, Shao-Chi, Resler, E. L., and Kantrowitz, Arthur: Electrical Conductivity of Highly Ionized Argon Produced by Shock Waves. Jour. Appl. Phys., vol. 26, no. 1, Jan. 1955, pp. 95-109.

TABLE I. - THERMAL CONDUCTIVITY OF ARGON

Temperature, T, °K	Thermal conductivity, k, cal/(cm)(sec)(°K)	
	Best estimate (a)	Lower limit (b)
300	4.24×10^{-5}	4.24×10^{-5}
400	5.33	5.32
500	6.28	6.27
600	7.15	7.12
700	7.97	7.91
800	8.74	8.63
900	9.48	9.31
1,000	10.2	9.95
1,500	13.4	12.70
2,000	16.3	14.98
2,500	19.0	16.97
3,000	21.5	18.75
4,000	26.3	21.90
5,000	30.9	24.65
6,000	35.2	27.12
7,000	39.4	29.39
8,000	43.5	31.50
9,000	47.4	33.47
10,000	51.2	35.33

[a]From viscosity and molecular beam data.

[b]$k = 3.582 \times 10^{-6} \, T^{3/2}/(139.04 + T)$.

TABLE II. - SHOCK-TUBE DATA FOR ARGON

Initial argon pressure, p, mm Hg	Incident shock-wave Mach number	Final equilibrium pressure, p_∞, atm	Final equilibrium temperature, T_∞ ^oK	Glass plate temperature rise, $T_f - T_0$ ^oK (a)	$\frac{T_f - T_0}{\sqrt{p_\infty}}$, $^oK/atm^{1/2}$
3	6.12	1.015	8580	18.9	18.8
3	6.07	.997	8480	18.9	19.0
5	5.80	1.50	7680	18.6	15.2
10	5.02	2.16	5780	17.2	11.7
20	4.30	3.04	4290	16.1	9.24
50	3.80	5.68	3390	18.6	7.82
50	3.74	5.45	3280	17.6	7.54
3	3.67	.31	3180	3.98	7.15
5	3.46	.45	2830	4.43	6.61
10	3.37	.84	2690	5.33	5.82
100	3.29	7.90	2560	17.2	6.12
10	3.14	.70	2350	4.61	5.52
10	2.94	.59	2070	3.40	4.43
20	2.88	1.12	2010	5.24	4.95
10	2.82	.53	1920	3.00	4.12
200	2.81	10.5	1920	14.5	4.48
10	2.62	.43	1690	2.13	3.25
50	2.56	2.03	1610	5.45	3.82
400	2.43	13.7	1440	12.1	3.27
400	2.40	13.4	1430	11.8	3.22
100	2.36	3.23	1380	5.65	3.14
100	2.29	2.96	1310	4.90	2.84
200	2.01	3.98	1045	4.51	2.26
400	1.85	6.26	910	4.25	1.70
400	1.86	6.26	910	4.70	1.88
400	1.84	6.04	910	4.70	1.91
400	1.76	5.36	835	3.64	1.57
750	1.55	6.42	665	2.87	1.13

[a]Interface temperature, T_f; initial temperature, T_0.

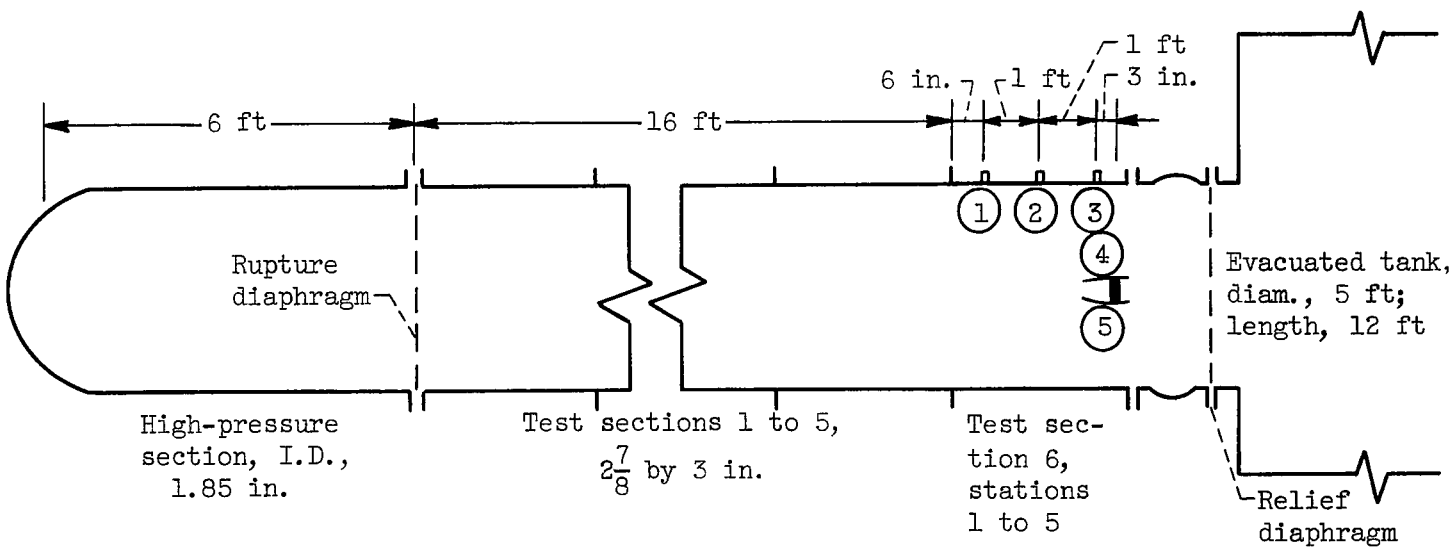

Figure 1. - Schematic diagram of shock tube. Piezoelectric shock detectors at stations 1 to 4; resistance thermometer at station 5.

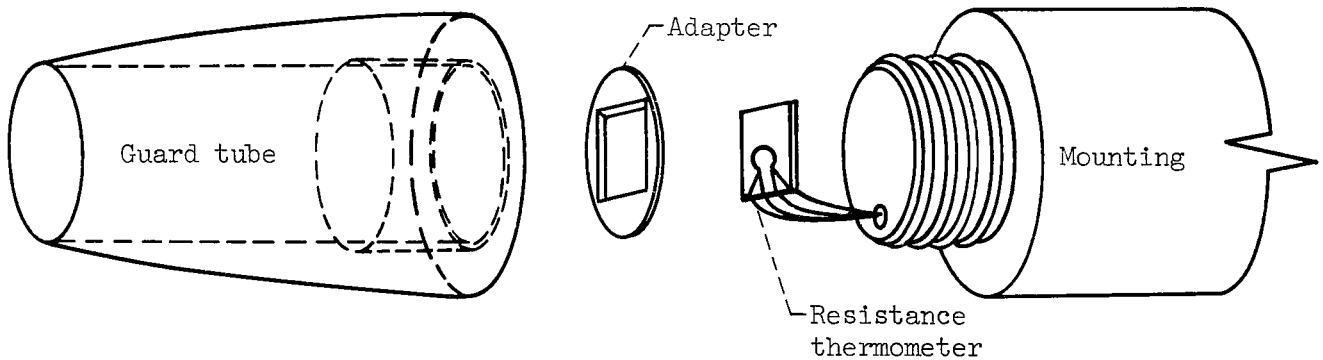

Figure 2. - Schematic drawing of thin-film resistance thermometer and mounting.

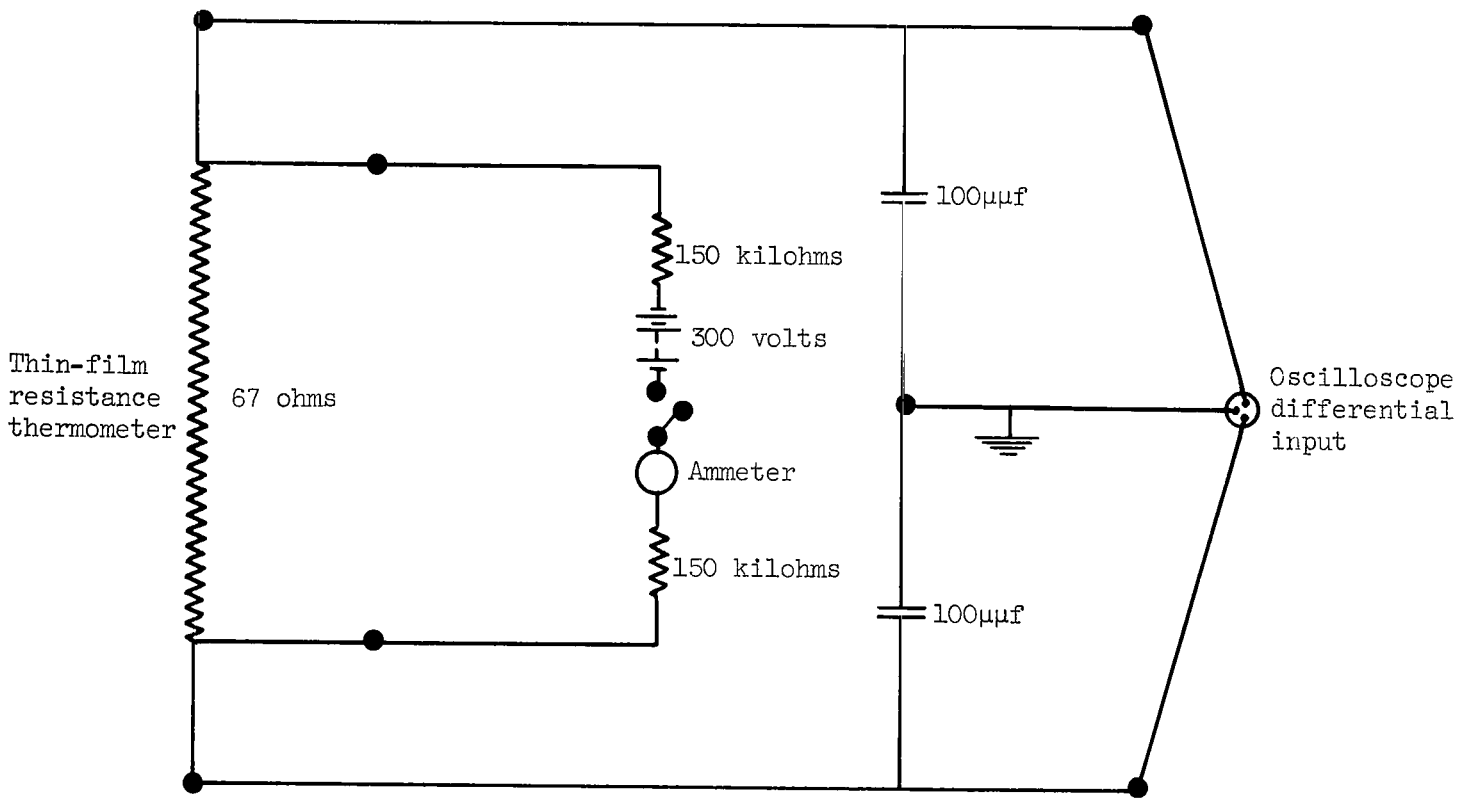

Figure 3. - Resistance-thermometer circuit.

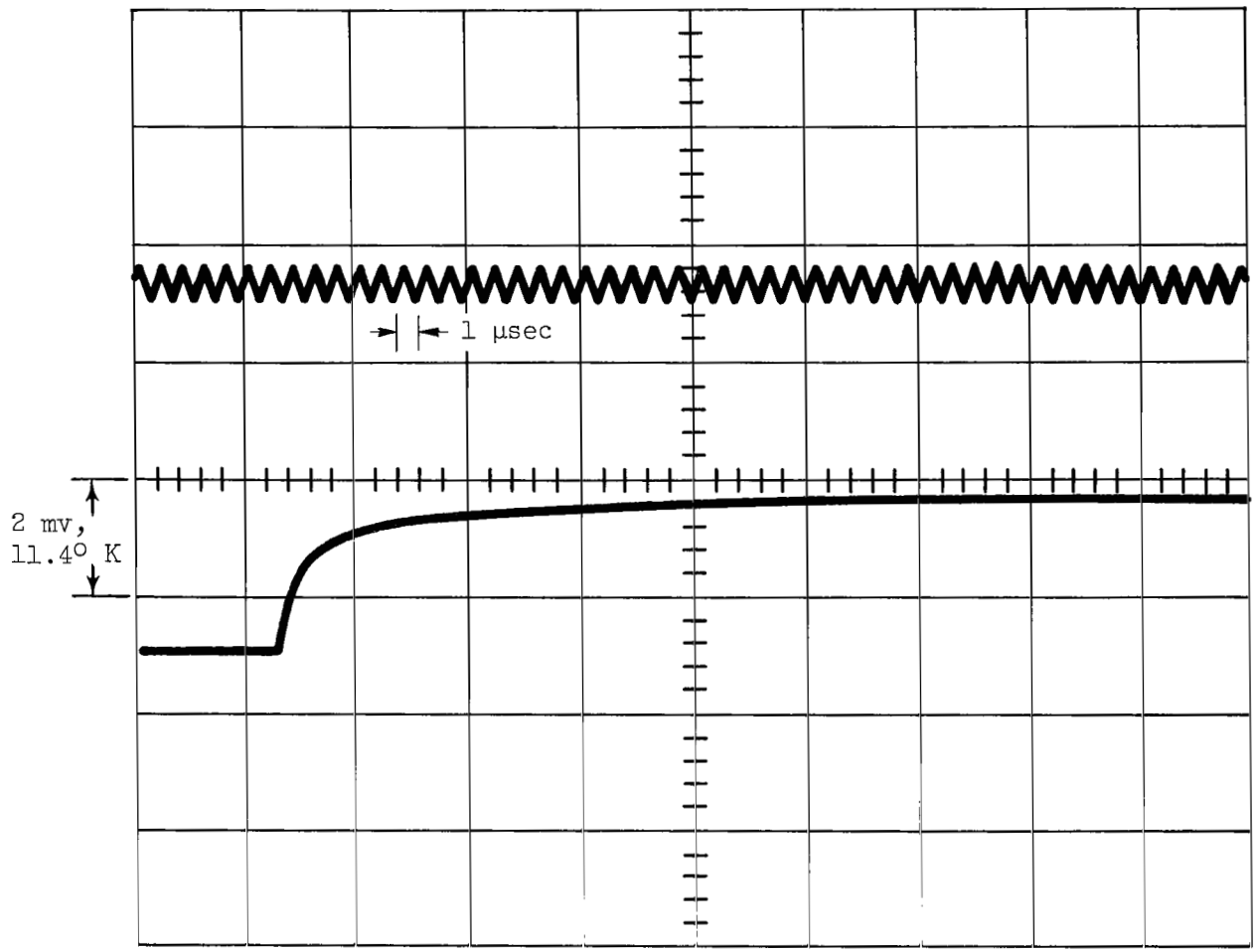

Figure 4. - Typical resistance-thermometer oscilloscope trace. Glass at 300° K exposed to pressure of 5.45 atmospheres of argon at 3280° K.

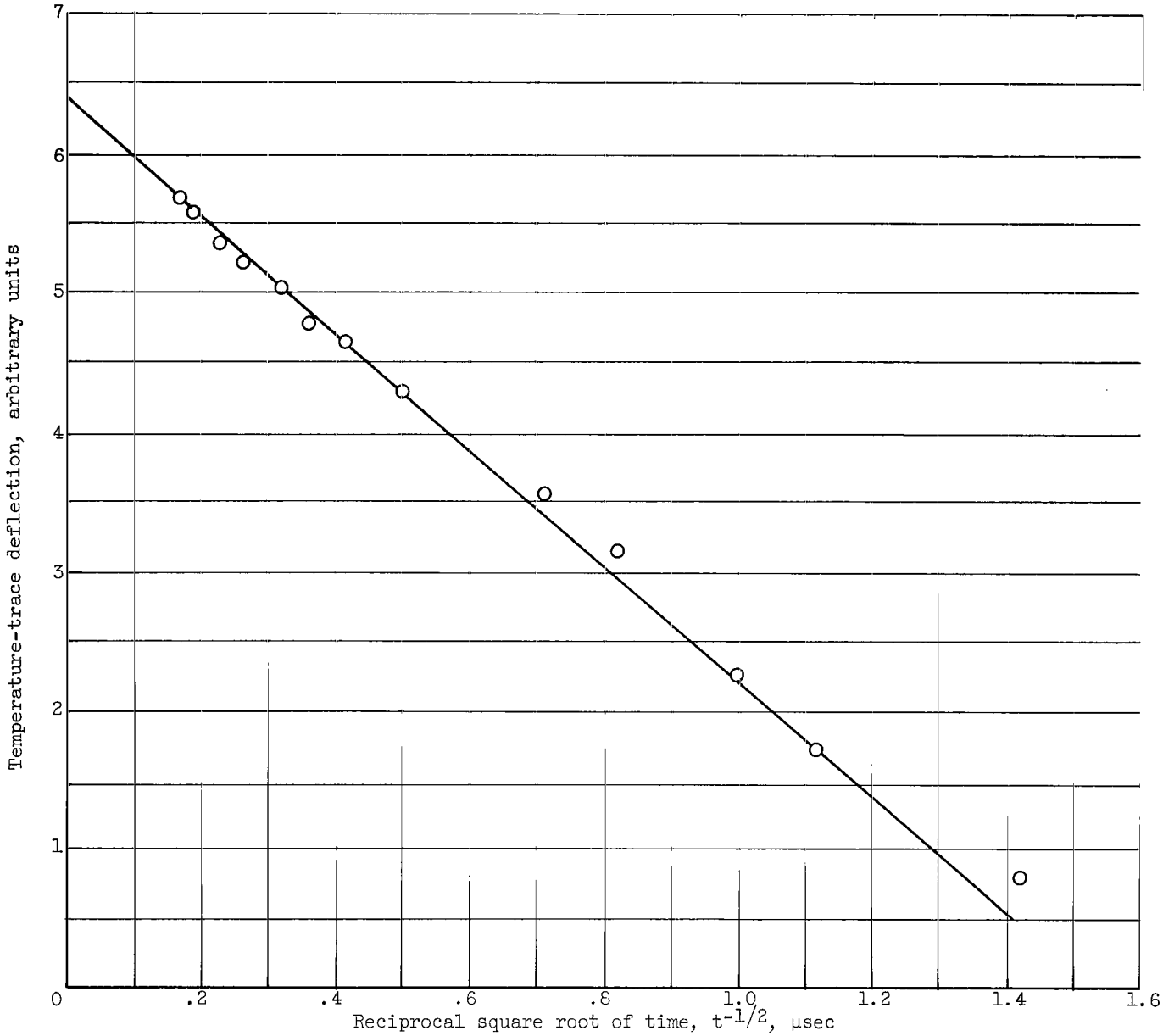

Figure 5. - Typical temperature-trace deflection. Glass at 300° K exposed to pressure of 5.45 atmospheres of argon at 3280° K; 0.360 unit of deflection corresponds to 1° K.

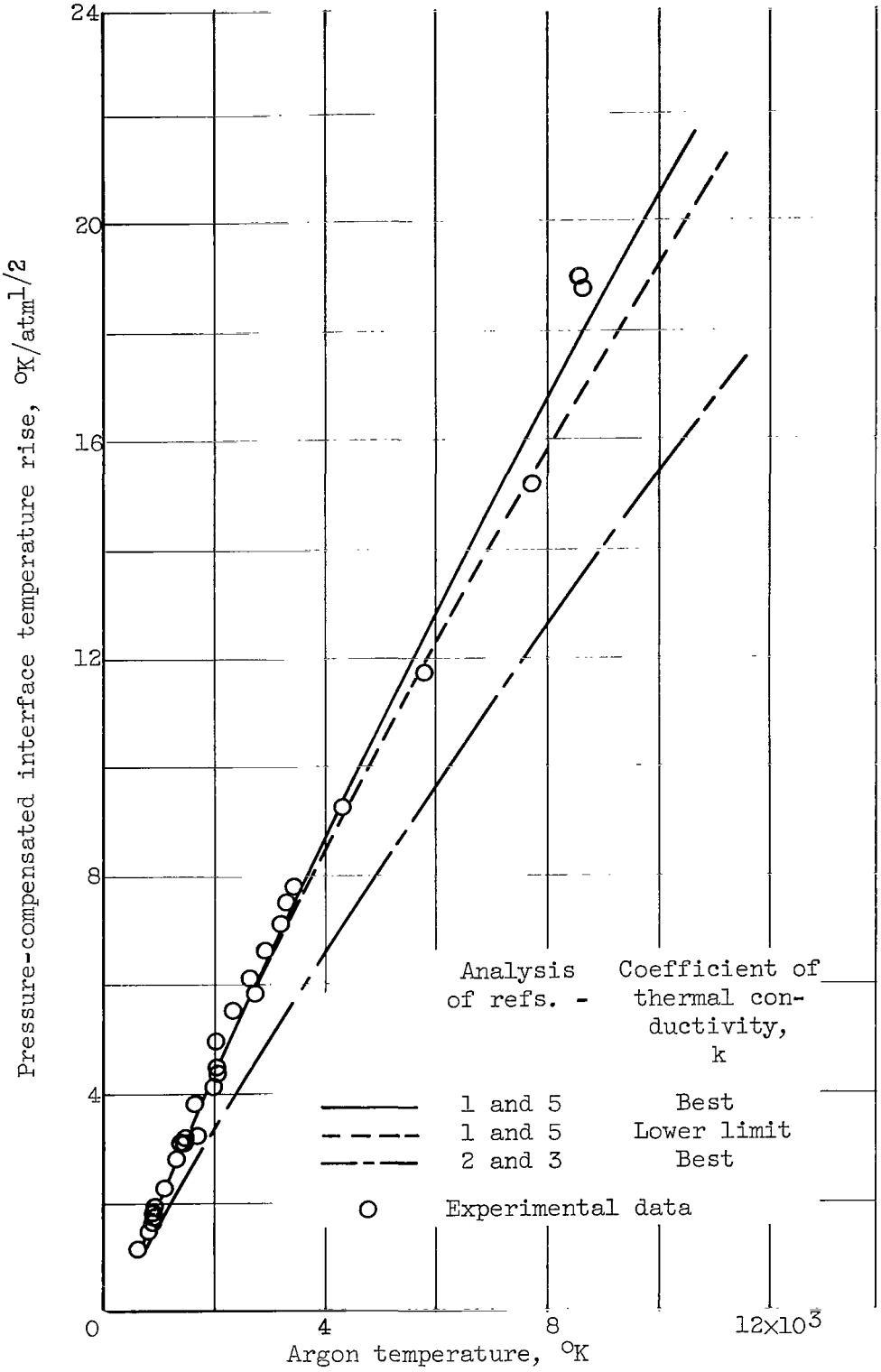

Figure 6. - Solutions for heat transfer from argon to glass.

NASA-Langley, 1964 E-1757